March 1, 1966 R. E. DACEY 3,238,484

D-CORES WITH ASSOCIATED WINDINGS FOR PRODUCING HIGH Q

Filed May 16, 1963

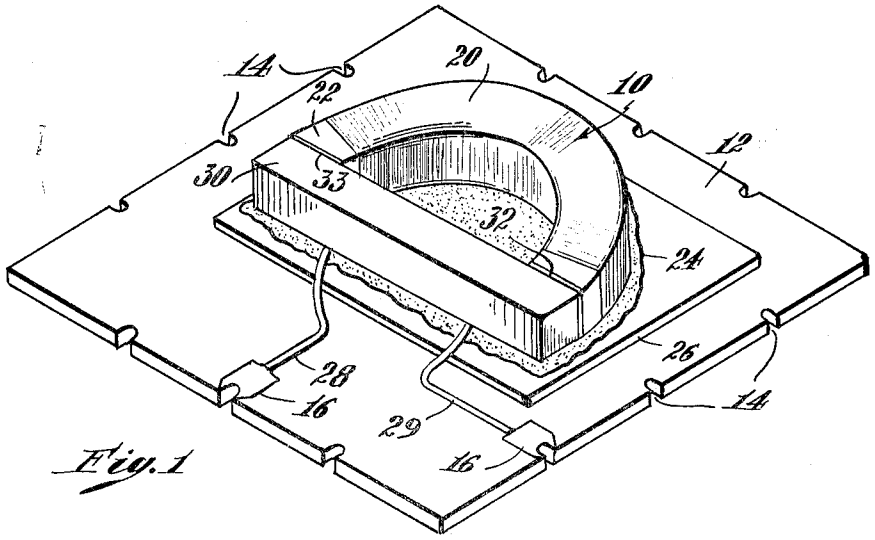


Fig. 1

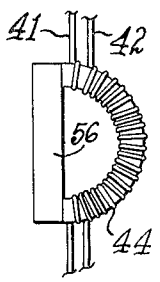


Fig. 2a

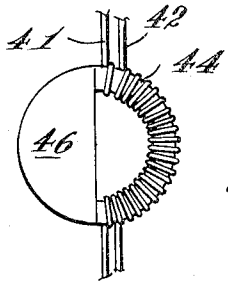


Fig. 2

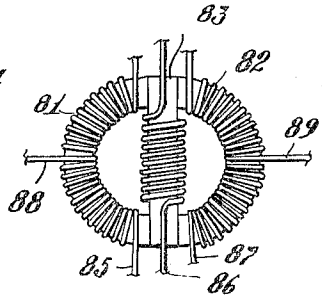


Fig. 4

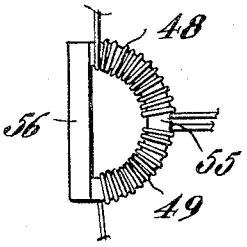


Fig. 3

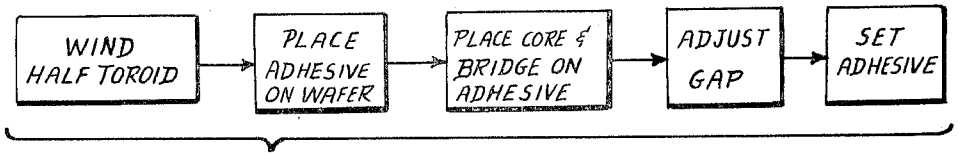


Fig. 7

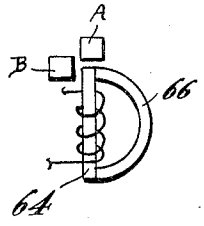


Fig. 5

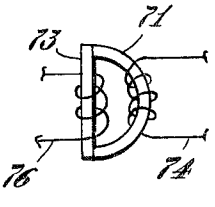


Fig. 6

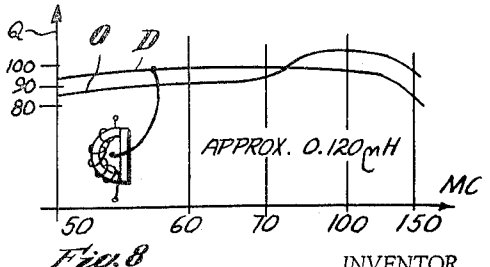


Fig. 8

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D-CORES WITH ASSOCIATED WINDINGS FOR PRODUCING HIGH Q

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The field of utility of this invention is electrical inductors and more particularly that of miniature inductor structures for use in micro-module circuit assemblies.

From the standpoint of electrical characteristics, the theoretically ideal form for inductance devices is a toroid. However, toroid coils and transformers are difficult and expensive to construct, particularly in small sizes, mainly because of the difficulty in applying multiwinding to completely closed toroidal cores in mass production; hence their general use has not been possible.

Objects and advantages of the invention are to provide inductance devices, principally for use in high frequency ranges, which compare favorably with strictly toroidal inductors as to electrical characteristics but which can be constructed at lower cost and with less difficulty. Further objects are to provide such inductance devices which exhibit a high Q, have negligible external fields, have no bias or drive sensitivity effects, permit high inductance values for an element of given volume, yield tight coupling between winding turns, are adapted for use in modular constructions, and which can be built in various final inductor configurations from a single basic core configuration. A still further object is to provide a method of high volume, quality consistent production of inductors of a precisely predetermined and consistent inductance value.

The nature and substance of the invention may be shortly stated as being based on the utilization of open and hence easily wound core members in such a manner that their discontinuous configuration has a minimal effect on the reluctance distribution thereon. In a true toroid, the complete absence of discontinuities in the magnetic path and winding configuration makes the reluctance drop caused by the passage of flux through the core equal to the magnetomotive force generated by the windings for each unit length of the magnetic path. The present invention, while contemplating the use of some core discontinuities so as to permit an economical winding process, minimizes the deleterious effect of these discontinuities by a peculiar correlation of sectional, preferably semitoroidal cores, of core bridges or magnetic shunts, and of windings or coils associated therewith in peculiar manner proved to be superior to other arrangements.

In one principal aspect the invention contemplates an inductance device with an open, arched magnetic core member of substantially uniform cross sectional area with two ends separated by an opening of appreciable width sufficient for the convenient application to the arched member of one or more windings or coils, by direct winding or slipping on a prewound coil. The opening of the arched core member is closed through a second magnetic core member directly connecting the ends of the arched magnetic core member over the opening but remaining bare, without winding. This structure is herein also referred to as D-core.

In another important aspect the invention provides a method of making an inductance device by applying a coil structure to an arched magnetic core member of substantially uniform cross sectional area and having two ends, by then applying a magnetic bridge member directly across the ends of the arched core member, by then adjusting the spacing between the bridge member and the

arched member until the winding exhibits of a predetermined valve of inductance, and by finally fixating the relative position of arched and bridge members, thus making the adjusted D-shaped core juncture permanent.

These and other objects and aspects of the substance of the invention will appear, together with various advantages and new results, from the herein presented outline of its principles, its mode of operation and its practical possibilities, together with a description of several typical embodiments illustrating its novel characteristics.

The description refers to the drawing in which

FIG. 1 is an isometric view of a preferred form of inductor according to the invention, incorporated in a micromodule assembly;

FIG. 2 is a plan view of a bifilar coil transformer including a modification in the core structure according to the invention;

FIG. 2*a* is a plan view, similar to FIG. 2, with a rectilinear instead of halfmoon shaped bridging core;

FIG. 3 is a plan view of a transformer modification with individual coils;

FIG. 4 is a plan view of duplex half toroid inductor with bridge, for low frequency use;

FIGS. 5 and 6 are diagrams of inferior half toroid indicators, presented for purposes of explaining the invention;

FIG. 7 is a flow diagram of a method of making inductors according to the invention; and

FIG. 8 is a diagram illustrating the performance of inductors according to the invention.

FIG. 1 shows an inductance device **10** according to the invention mounted on a ceramic wafer **12** of the type used in building up so-called micromodular electronic assemblies. These wafers are typically square and have along each edge a plurality of notches **14** into which interconnecting riser wires can be inserted. Selected ones of the notches **14** are provided with solder terminals **16** for use, as needed, in connecting corresponding electrical components carried by the wafer into the module circuitry.

In the illustrated inductance device **10**, a coil **20** is wound in evenly distributed fashion on a semitoroidal magnetic core **22** having two ends separated by an opening of sufficient width for conveniently applying a winding. The wound core is adhered to the wafer **12** by suitable means, for example a chemically setting epoxy adhesive indicated at **24**. For securing a good bond with conventional ceramic wafers it has been found beneficial to apply Mylar type **26** thereto before cementing them to the cores **22**. The leads **28**, **29** to the coil **20** are soldered to adjacent ones of the terminals **16**.

Across the opening between the exposed ends of the semitoroid core **22** is place a paramagnetic shunt bar or bridge **30**. Similar to the core **22**, this bridge is also secured in place by adherence to the wafer **12** with suitable, such as epoxy, adhesive. Small adjustment gaps **32**, **33** are preferably provided between the bridge **30** and the semitoroidal core **22**, this bridge also secured in place by adherence to the wafer **12** with suitable, such as epoxy, adhesive. Small adjustment gaps **32**, **33** are preferably provide between the bridge **30** and the semitoroidal core **22**, the width of which is determined as set forth hereinbelow with reference to FIG. 7. The ends of the bridging bar **30** are preferably coplanar shown, and parallel to the coplanar ends of the arched core **10**.

A transformer according to the invention is shown in FIG. 2. In this device a pair of windings **41** and **42** are wound in bifilar relationship on a semitoroidal magnetic core member **44**, similar to core **22** of FIG. 1. The magnetic circuit is completed through a semicircular magnetic bridge **46** placed across the ends of the semi-

toroid 44. The semicircular bridge 46 provides a smoothly continuous shunt path for magnetic flux from the ends of the member 44. Magnetic circuits of this shape can also be utilized for transformers with separate windings, and for single winding inductors. This modification is sometimes preferable for mechanical such as module matching reasons of assembly techniques, and its performance might be slightly better than that of a rectangular bridge core device depending on the frequency. However its cost of fabrication is somewhat higher than the straight magnetic bridging member 30 illustrated in FIG. 1 which gives comparably satisfactory results.

While bifilar winding is of course preferable, satisfactory results can be obtained in many instances with separate windings. Such windings are shown in FIG. 3 at 48 and 49 as applied to a semitoroidal core 55 having a straight bridging member 56 of the type shown in FIG. 1.

FIG. 2*a* shows a transformer with a straight bridge 56 according to FIG. 1 and a bifilar winding 44 according to FIG. 2. It will be noted that the bridging members are generally speaking segmental relatively to the openings of the curved cores, but it will be understood that these curved cores are not necesarily semicircular but may have functionally analogous shapes.

While not all the reasons for the excellent performance of D-core structures according to the present invention are fully understood at this time, it is believed that these favorable characteristics can be explained as follows.

Semitoroidal cores uniformly wound over their entire length of uniform cross-section confine uniform magnetic flux practically without stray, each turn being tightly coupled to the others. The magnetic potential difference between the very ends of the semitoroid is shunted as directly as possible by a bridge member such as 30 of FIG. 1. The term "directly" as used hereinafter and in the claims should be understood to means an essentially straight magnetic path between, and completely covering, the two ends of a D-core without deviation or interruption excepting a small gap which is adjustable for calibrating purposes.

It has been experimentally established that D-cores wound according to FIG. 1 or FIG. 3, respectively, exhibit a considerable Q deterioration if the coil is on the bridge or yoke 30. It seems that more stray flux is generated by a coil on the bridge of a D-core structure, as compared to similar cores wound only on the curved portion, which latter do not essentially differ in this respect from completely toroidal structures. This can be shown by testing an inductor according to FIG. 5 with a winding 64 on the bridge, with a bare semitoroidal D-core 66 and with a shield placed either at A or B respectively. Such shields are conductive non-magnetic bodies capable of absorbing energy in the form of eddy currents. This energy can be measured with thermocouples, and it appears that the Q drops considerably with the shield at A, but does not drop appreciably with the shield at B. While the magnetic circuit appears superficially to be the same whether a winding is on the straight bridge or on the longer, curved, arch core, the magnetic potential developed along the winding is faced with a much longer shunt path through the curved core member and hence the stray flux energy originating at A of FIG. 5 would be greater than that at B if the winding were on the curved semicircular D-core portion. This explains the difference in performance between arch wound D-cores according to FIG. 1 and bridge or yoke wound D-cores according to FIG. 5. Structures as schematically illustrated in FIG. 5 are outright inferior, whereas structures according to FIG. 6 are somewhat better but still inferior to structures according to FIGS. 1 and 3. No difference however was found in the performance between curved bridge and straight bridge structures in accordance with FIGS. 2 and 3 respectively.

According to the above rule, structures which might be called double D-cores such as shown in FIG. 4 should be inferior. However it was found somewhat unexpectedly that in the same frequency range they perform somewhat between FIGS. 5 and 6. Bridge divided full toriods, or double D toriods, according to FIG. 4 are particularly useful in discriminator circuitry with one winding on the bridge and a split winding on each arch. FIG. 4 illustrates such a transformer.

In FIG. 4, numerals 81 and 82 denote the two semitoroid core structures, 83 is the direct, straight, bridge, and 85, 86 and 87 are respective windings, windings 85 and 87 having center taps 88, 89, respectively.

It should be understood that these windings or some of them can be bifilar, and that winding 86 can be omitted. As a matter of fact structures according to FIG. 4 exhibit less Q deterioration if the winding 86 is omitted, and such bridged double D structures are superior to composite toroid structures without direct bridge and quite useful, although only for low frequencies as distinct from the structures according to FIGS. 1 to 3 which are equally efficient at high and very high frequencies.

While attempts have been made previously to approach the electrical performance of continuous true toroids by winding two semitoroids separately and then bringing the ends of the two halves together, it is very difficult to avoid some discontinuity at the junction and thus these structures, though they closely resemble true toroids in appearance, tend to exhibit considerable stray flux with its attendant loss of coupling between turns and drop in Q. This is avoided by bridges according to FIG. 4.

Another attempt of explaining the phenomena set forth above takes into consideration the beneficial effect of keeping all windings on one core piece such that no discontinuities are introduced between any of the turns which would tend to reduce the coupling between them.

As mentioned above, it was experimentally found that the performance of structures according to the invention comes very close to that of true fully continuous toroid core inductors. Indeed, structures with transverse bridges according to FIGS. 1 to 3, if statically shielded have been found to be even better than pure toroid inductors with regard to Q deterioration. Such shielded structures have a Q of 100 or greater or L values of 1 μh. to 0.5 μh. The repeatability for gaps adjusted as will be described hereinbelow, was very good such as from 5 to 10% from 1 to 0.07 μh., at frequencies of from 100 to 150 mc. Comparative tests for ΔL versus ΔI for D and perfect toroid cores, respectively, show differences of approximately 5%. Tests for temperature rise versus current indicated that at 72° F. ambient temperature the temperature rise was not higher than to 85° F. at 2500 ma.; generally speaking the temperature rise was in such comparative tests never more than approximately 15° F. The diagram FIG. 8 illustrates these comparative qualities of D and pure toroid structures, the curve for a D-core inductor according to the invention being marked D and that for a continuous full toroid of comparable size and winding being marked O. In this diagram the frequency is plotted on a logarithmic scale and the Q on a linear scale. Both curves were taken at approximately 0.1 μh., in shielded state. A comparison between L and Q values without shielding and with shielding, according to the formula

$$\Delta L \text{ or } \Delta Q = \left(100\% \frac{L \text{ or } Q \text{ after shielding}}{L \text{ or } Q \text{ before shielding}}\right) = 100\%$$

indicated in randomly selected tests that for D-cores the ΔL under the above stated conditions was -7% and that the ΔQ was -10%, whereas the corresponding values for pure toroids were $\Delta L = -7.8\%$ and $\Delta Q = -8.0\%$.

In a practically very important aspect of the invention the magnetic circuit structure illustrated in FIG. 1 facilitates the achievement of very precisely defined values of inductance within micromodule constructions of the type shown. To provide a particular inductance the steps illustrated diagrammatically in FIG. 7 are performed as follows.

A semitoroid is first wound with an appropriate num-

ber of turns and is then adhered to a wafer or other suitable base with a settable adhesive such as one of the well-known epoxy compounds. The coil leasd are first soldered to the appropriate terminals. An appropriate test device for measuring inductance is then connected to the terminals, and, before the cement sets, the bridge member is placed on the wafer adjacent to the ends of the semitoroid D-core. While the coil is under test and before the adhesive sets, the width of the gap between the bridge and the semitoroid is adjusted empirically until the desired value of inductance is obtained, when the coil may be disconnected from the test device. The adhesive is then caused to set which, in the case of many epoxy compounds, involved merely allowing the assembly to sit undisturbed for an appropriate length of time.

As an illustration of actual practical performances obtainable with this mode of construction typical for all embodiments herein described, the following values are representative. For an inductor according to FIG. 1, having a core of powdered iron powder (such as that known as Carbonyl "W"), a maximum diameter equal to the length of the bridge **30** of 0.203 inch, a cross sectional area throughout the magnetic circuit of approximately 0.0025 square inch, and wound as shown with 20 turns of #36 wire, an inductance of close to 1.0 μh. at a Q of better than 80 can be expected. The exact values of inductance desired were obtained by adjusting the gaps **32, 33** as above described. This electrical performance is substantially equal to that of a comparable complete toroid at a given measuring frequency. The performance of a true solenoid begins to exceed that of devices according to the invention only as the upper frequency limit for the magnetic core material used is approached.

It will be understood that the use of D-cores according to the invention may often be advantageous even if the electrical performance is somewhat inferior, due to the fact that as compared to full toroid windings the winding of half toroids is much easier. It will be further understood that, while the winding of the straight or bridge part would be even easier, this is undesirable within the context of the present invention.

It will be further understood that the arched core structures according to the invention does not have to be strictly seimtoroidal and that the bridge means does not have to be strictly flat on the side where it covers the ends of the arched core member. Admissible slight deviations from the shapes shown are permissible, so long as measurements such as above outlined indicate that the required performance data are present.

It should be understood that the present disclosure is for the purpose of illustration only and that this invention includes all modifications and equivalents which fall within the scope of the appended claims.

I claim:

1. An inductor assembly comprising:

an arched magnetic core member having two ends separated by an opening of appreciable width sufficient for the convenient application of winding means to the core member;

winding means on said arched member;

a base member for supporting said arched magnetic core member and said winding;

a second magnetic core member for bridging the ends of said magnetic core member; and

settable adhesive means for securing said core members to said base member in spaced relation to the ends of said arched magnetic core member, said spaced relation being predetermined to regulate the inductance of said winding means to a predetermined value.

2. An inductance device comprising:

only one semitoroidal magnetic core member having diametrically opposite ends;

winding means on said core member;

a separate rectangularly parallelepipedal straight magnetic bar member for bridging said ends of the core member and having faces fitting said ends of the core member; and

said opposite ends of said core member and said faces of the bar member each being separated by a minimal gap of uniform thickness set for an inductance value providing minimal stray flux.

3. An inductor assembly according to claim **2**, further comprising a base member supporting said semitoroidal core member, said winding means, and said bar member and extending therebeyond.

4. An inductance device comprising:

a single semitoroidal magnetic core member having diametrically opposite ends;

winding means on said core member;

a separate straight magnetic bar member bridging said ends of the core member;

a separate second semitoroidal magnetic core member completing a full toroid on the side of bar member opposite of the first core member; and

winding means on said second core member.

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